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Active teleportation of a quantum bit

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We report the experimental realization of the "active" quantum teleportation (QST) of a one-particle entangled qubit. This demonstration completes the original QST protocol and renders it available for actual implementation in quantum computation networks. It is accomplished by implementing an 8 m optical delay line and a single-photon triggered fast electro-optic Pockels cell. A large value of teleportation "fidelity" was attained: $F_a = (90 \mp 2)\%$. Our work follows the line recently suggested by H. W. Lee and J. Kim [Phys. Rev. A **63**, 012305 (2000)] and E. Knill, R. Laflamme, and G. Milburn [Nature (London) **409**, 46 (2001)].

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Quantum state teleportation (QST), introduced by Bennett, Brassard, Crepeau, Jozsa, Peres, and Wootters came to be recognized in the past decade as a fundamental method of quantum communication and, more generally, as one of the basic ideas of the whole field of quantum information [1]. Following the original teleportation paper and its continuous-variables version [2] an intensive experimental effort started for the practical realization of teleportation. Quantum state teleportation (QST) was in fact realized in a number of experiments [3,4] and [5]. Very recently a "qubit teleportation" with an unprecedented large "fidelity" ($F \approx 0.95$) has been experimentally demonstrated by our laboratory in the context of quantum optics by adoption of the concept of "entanglement of one photon with the vacuum" by which each quantum superposition state, i.e., a *qubit* was physically implemented by a two dimensional subspace of Fock states of a mode of the electromagnetic field, specifically the space spanned by the QED "vacuum" and the 1-photon state [6]. Precisely, if A and B represent two different modes of the field, with wave vectors k_A and k_B directed respectively towards two distant stations (Alice and Bob), these ones may be linked by a nonlocal channel expressed by an entangled state implying the quantum superposition of a *single photon*, e.g., by the *singlet*: $|\Phi\rangle_{singlet} = 2^{-1/2}(|1\rangle_A|0\rangle_B - |0\rangle_A|1\rangle_B)$. Here the mode indices 0 and 1 denote respectively the vacuum and 1-photon Fock state population of the modes k_A, k_B and the superposition state may be simply provided by an optical *beam splitter* (BS), as we shall see. The relevant conceptual novelty introduced here consists of the fact that the *field's modes* rather than the photons associated with them are taken as the information carriers, i.e., *qubits*. Furthermore here a proper use is made of the concept of "single-photon nonlocality," a paradigm first introduced by Albert Einstein in a context close to the formulation of the EPR "paradox" [7,8] and later elaborated by [9–12]. Our scheme was designed by adapting the methods proposed recently by Knill *et al.* [13] and by Duan *et al.* [14].

All these previous QST realizations nevertheless correspond to highly simplified, *incomplete* "passive" schemes by which the success of the protocol is demonstrated indirectly by the mere detection of the nonlocal correlations established a posteriori between the extreme stations, Alice and Bob. These *passive* realizations intended for mere demonstration have the advantage of avoiding the difficult implementation of the final stage of QST, i.e., of the unitary transformations U restoring the *exact* input qubit at Bob's site under Alice's control through the QST *local channel* [1]. The main problem faced here is due to the relatively long time T needed to switch, under *single-photon* excitation by the Alice's Bell-measurement apparatus the high-voltage (HV) pulses driving the electro-optic Pockels cells (EOP) which implement the necessary U unitaries at Bob's site. Of course, in order to preserve an appreciable QST *fidelity* it must be $T \ll \tau$, τ being the characteristic time of the decoherence process affecting the *nonlocal channel*, i.e., the one that dephases the corresponding entangled $|\Phi\rangle_{singlet}$ [1]. The present work realizes the *complete*, i.e., *active* qubit teleportation process by completing the corresponding optical scheme according to the standard QST protocol [1]. As a basic qubit-QST scheme, the quoted vacuum-1 photon configuration was adopted [6].

The experimental setup, Fig. 1, can be somewhat considered to be the "folded" configuration of the one reported in [6]. The significant changes consisted of the addition of the optical delay line (DL) and of a different measurement apparatus at Bob's site. Let us briefly outline the details of the apparatus. A nonlinear (NL) $LiIO_3$ crystal slab, 1.5 mm thick

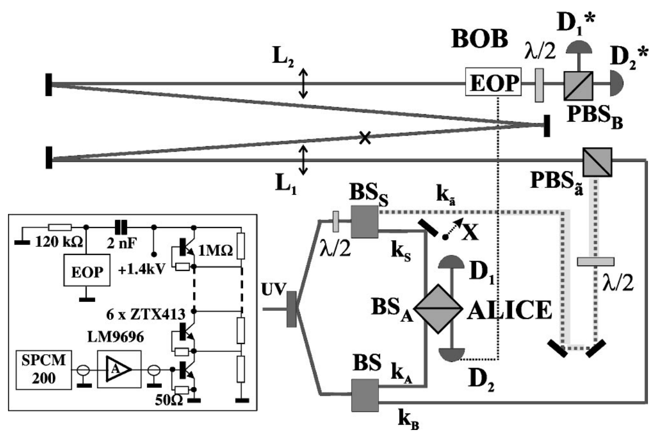

FIG. 1. Experimental apparatus realizing the "active" quantum state teleportation protocol (QST).The cross close to the center of the optical delay line indicates the approximate position of the focal region of the lens L_1. Inset: Diagram of the fast electronic switch of the electro-optic Pockels cell (EOP) implementing the unitary transformation: $U \equiv \sigma_z$.

with parallel antireflection coated faces, cut for type I phase matching was excited by a single mode UV cw argon laser with wavelength $\lambda_p = 363.8$ nm and with an average power $\simeq 100$ mW. The two photons belonging to each correlated pair emitted by spontaneous parametric down conversion (SPDC) with the same linear vertical (V) polarization had equal wavelengths $\lambda = 727.6$ nm and were spatially selected by equal pinholes with diameter 0.5 mm placed at a distance of 50 cm from the NL crystal. Of course, the product state condition of each SPDC pair, $|\Phi\rangle_{out} = |1\rangle_A \otimes |1\rangle_S$, did not imply any mutual nonlocal correlation between the particles. Indeed for our purpose the particles could have been emitted by two totally independent sources. By two beam splitters devices BS and BS_S, each composed by a combination of a $\lambda/2$ plate + a calcite crystal and inserted on the output modes of the SPDC source, $|\Phi\rangle_{out}$ was transformed into the product of two entangled states, $|\Phi\rangle_{singlet} = 2^{-1/2}(|1\rangle_A|0\rangle_B - |0\rangle_A|1\rangle_B)$ and $|\Psi\rangle_{S\tilde{a}} = (\bar{\alpha}|1\rangle_S|0\rangle_{\tilde{a}} + \bar{\beta}|0\rangle_S|1\rangle_{\tilde{a}})$ with $\bar{\alpha}^2 + \bar{\beta}^2 = 1$, defined over the two pairs of the BS's output modes (k_A, k_B) and $(k_S, k_{\tilde{a}})$, respectively. Precisely, one photon of the SPDC pair excited the output modes k_A, k_B of the symmetrical, i.e., 50:50 beam splitter BS by the singlet state $|\Phi\rangle_{singlet}$ which provided the nonlocal teleportation channel. The output modes $k_S, k_{\tilde{a}}$ of the other, *variable* beam splitter BS_S were excited by the entangled state $|\Psi\rangle_{S\tilde{a}}$ giving rise to the *local* realization on the output mode k_S of the *unknown* qubit to be teleported: $|\Psi\rangle_{in} = (\alpha|0\rangle_S + \beta|1\rangle_S)$. This corresponded to the local realization on the mode $k_{\tilde{a}}$ of a related "ancilla" state $|\Psi\rangle_{\tilde{a}} = (\gamma|0\rangle_{\tilde{a}} + \delta|1\rangle_{\tilde{a}})$ that will be adopted here for the verification of the QST success, as we shall see. Most important, the "ancilla" provided in our system the synchronizing "clock" signal that has been recognized to be a necessary ingredient of every quantum computing network when single-photon *qubits* and *e-bits* are involved [6,13,14]. At Alice's site, the modes k_A and k_S were linearly superimposed by a common 50:50 beam splitter BS_A whose output modes k_1, k_2 excited the Bell-measurement apparatus, consisting of the detectors D_1, D_2. Micrometric changes of the mutual phase φ of the interfering k_S and k_A modes were obtained by a piezoelectrically driven mirror placed at the exit of BS_S. All detectors in the experiment were Si-avalanche EG&G-SPCM200 modules having equal quantum efficiencies, ≈ 0.45. The beams were filtered before detection by interference filters within a bandwidth $\Delta\lambda = 6$ nm.

The apparatus at the Alice site, consisting of BS_A, D_1, D_2 performed a standard Bell-state measurement with 50% efficiency. Precisely, the Bell states $|\Psi^3\rangle_{SA} = 2^{-1/2}(|0\rangle_S|1\rangle_A - |1\rangle_S|0\rangle_A)$ and $|\Psi^4\rangle_{SA} = 2^{-1/2}(|0\rangle_S|1\rangle_A + |1\rangle_S|0\rangle_A)$ implying the teleportation of a single-photon qubit, could be singled out by our scheme [6]. The other two Bell states involving measurements at Alice's of either zero or two photons $|\Psi^1\rangle_{SA} = |0\rangle_S|0\rangle_A$, $|\Psi^2\rangle_{SA} = |1\rangle_S|1\rangle_A$ were not identified by the apparatus, as expected for any linear detection system [15]. Furthermore, it could be easily checked by carrying out formally the product $|\Psi\rangle_{total} = |\Psi\rangle_{in}|\Phi\rangle_{singlet}$ that a single photodetection, a "click" by D_1, i.e., the realization over the BS_B output mode set (k_1, k_2) of the state $|1\rangle_1|0\rangle_2 = |\Psi^3\rangle_{SA}$, implied the realization at Bob's site of the state $(\alpha|0\rangle_B + \beta|1\rangle_B)$, i.e., of the *exact* teleported copy of the input state $|\Psi\rangle_{in}$. Alternatively, a click at D_2 expressing the realization of the state $|0\rangle_1|1\rangle_2 = |\Psi^4\rangle_{SA}$ implied the realization at Bob's site of the state $(\alpha|0\rangle_B - \beta|1\rangle_B) = \sigma_z|\Psi\rangle_{in}$. Since $\sigma_z^2 = I$, the complete QST protocol could be achieved in our experiment by allowing the direct activation by D_2 of an electro-optic (EO) device performing at Bob's site the unitary transformation $U \equiv \sigma_z$. This transformation was implemented in the experiment by a $LiNbO_3$ high-voltage micro Pockels cell (EOP) made by Shangai Institute of Ceramics with <1 nsec risetime. The EOP $\lambda/2$ voltage, i.e., leading to a $\lambda/2$ EO-induced phase shift of the single-photon state $\beta|1\rangle$ respect to the (phase-insensitive) vacuum state $\alpha|0\rangle_B$ appearing in the expression of $(\sigma_z|\Psi\rangle_{in})$, was $V_{\lambda/2} = 1.4kV$. The difficult problem of realizing a very fast electronic circuit transforming each small ($\simeq 1$ mV) Si-avalanche photodetection signal into a calibrated fast pulse in the kV range was solved, after testing many sophisticated circuits, by the simplest one consisting of single linear amplifier chip (LM9696) exciting directly a single chain of six very fast avalanche transistors (Zetex ZXT413: cf Fig. 1, inset). A careful selection and wiring of the active components was found decisive for minimizing the overall risetime of the device: 22 nsec. This corresponded to the minimum delay we must impart to the teleported single photon state $(\sigma_z|\Psi\rangle_{in})$ before entering EOP in order to be transformed into the wanted state $|\Psi\rangle_{in}$. The optical DL, 8 m long and corresponding to a delay $\Delta T = 26.6$ nsec $> T_r$, was realized by multiple reflections by three dielectric coated plane mirrors and by two antireflection coated high-quality lenses: L_1 with focal length 1.5 m and L_2 with focal lenght 0.3 m (cf. Fig. 1).

An efficient test of the success of the *active* qubit-QST operation was carried out by a "passive" interference procedure involving the synchronizing *clock* state, i.e., the "ancilla" state associated to the mode $k_{\tilde{a}}$. The beam carrying the "ancilla" state $|\Psi\rangle_{\tilde{a}}$ was injected into the main optical delay line by means of a polarizing beam splitter (PBS) and was made to fully spatially overlap the main teleportation beam, i.e., carrying the states $|\Psi\rangle_{in}$ and $(\sigma_z|\Psi\rangle_{in})$, but with *orthogonal* polarization respect to these ones. Precisely, the EO crystal of the Pockels cell was oriented in a direction such that the efficiency of the EO phase-shifting operation was maximum for the (V) polarization of the main teleported beams and zero for the horizontal (H) polarization of the "ancilla" beam.

At the exit of the EOP, the orthogonal linear polarizations of the two (teleported+ancilla) beams were first rotated by the same amount by means of a $\lambda/2$ plate, then linearly mixed by a polarizing beam splitter PBS_B and finally measured by the couple of verification detectors: D_1^*, D_2^*. The combination ($\lambda/2$plate$+PBS_B$) provided the *variable* beam-splitting action (BS_B) at Bob's site needed to implement the "passive" verification of the QST success through coincidence measurements involving the two detector sets (D_1, D_2) and (D_1^*, D_2^*). Assume for simplicity and with no loss of generality that both BS_S and BS_B were set in the *symmetrical* condition: i.e., with equal reflectivity and trans-

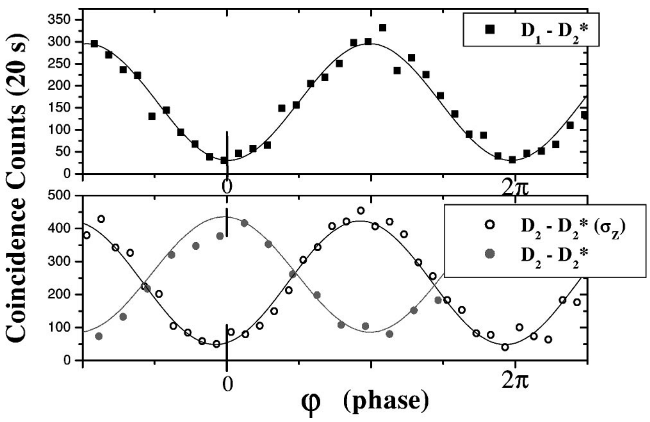

FIG. 2. Interferometric fringe patterns due to coincidence experiments involving different pairs of detectors within the *active* QST verification procedure upon variation of the phase φ of the measured fields. Upper plot: pattern related to the *exact* teleportation of the input state: $|\Psi\rangle_{in}$. Lower plot, full circles: teleportation of the state $(\sigma_z|\Psi\rangle_{in})$ with inhibition of the EOP operation. Lower plot, open circles: result of the transformation $U(\sigma_z|\Psi\rangle_{in})=|\Psi\rangle_{in}$ induced by the EOP activation by the Alice's detector D_2.

mittivity parameters: $|r|^2=|t|^2=\frac{1}{2}$. Let us vary the position $X=(2)^{-3/2}\lambda\varphi/\pi$ of the mirror at the exit of BS_B. By straightforward calculation the phase shift φ induced on the measured fields is found to affect the coincidence counts rates according to the following expressions [6]:

$$(D_1-D_2^*)=(D_2-D_1^*)=\frac{1}{2}\cos^2\frac{\varphi}{2},$$

$$(D_1-D_1^*)=(D_2-D_2^*)=\frac{1}{2}\sin^2\frac{\varphi}{2},$$

where $(D_i-D_j^*)$, $i,j=1,2$, expresses the probability of a coincidence detected by the pair D_i, D_j^* in correspondence with the realization at Alice's site either of the state $|\Psi^3\rangle_{SA}$, for $i\neq j$, or of the state: $|\Psi^4\rangle_{SA}$ for $i=j$. The realization of these states implied the corresponding realization at Bob's site of the teleported state $|\Psi\rangle_{in}$ or of the state $(\sigma_z|\Psi\rangle_{in})$, as said. The upper and lower plots shown in Fig. 2 correspond to the actual realization of these states. Precisely, the upper plot shows the experimental coincidence data corresponding to the direct realization at Bob's site of the teleported $|\Psi\rangle_{in}$. The data of the lower plot expressed by full circles correspond to the realization at Bob's site of the state $(\sigma_z|\Psi\rangle_{in})$ upon *inhibition* of the EOP action. However the data expressed by open circles, taken by previous EOP activation, correspond to the realization of the EOP-transformed state $U(\sigma_z|\Psi\rangle_{in})=|\Psi\rangle_{in}$, as shown by comparison with the upper plot. In summary, the results show that allowing the automatic actuation of the EOP switch by the Alice's detector D_2 results in the actual teleportation of the unknown input qubit $|\Psi\rangle_{in}$ *whenever* one of the detectors D_1, D_2 clicks, i.e., whenever a single photon is detected at Alice's site and another single photon is detected at Bob's site. Note that the above QST verification procedure involving the ancilla mode $k_{\tilde{a}}$ enabled a nearly *noise-free* teleportation procedure. Indeed, if no photons were detected at Alice's site, i.e. by D_1 and/or D_2, while photons were detected at Bob's site by D_1^* and/or D_2^* we could conclude that the ‘‘idle’’ Bell state $|\Psi^1\rangle_{SA}$ was created. If on the contrary no photons were detected at Bob's site while photons were detected at Alice's site, we could conclude that the other ‘‘idle’’ Bell state $|\Psi^2\rangle_{SA}$ was realized. The data collected in correspondence with these ‘‘idle’’ events were automatically discarded by the electronic coincidence circuit.

Note, interestingly, that the presence of the delay line did not impair substantially the value of the QST ‘‘fidelity,’’ as determined by the ‘‘visibility’’ V of the interference plots of Fig. 2: $F\equiv\langle\Phi_{in}|\rho_{out}|\Phi_{in}\rangle=(1+V)/2$. It was found that the very high value $F=(95.3\pm0.6)\%$ previously attained by the *passive* method was reduced by the present DL decoherence to the figure: $F_a=(90\pm2)\%$, still largely overcoming the limit value implied by genuine quantum teleportation [3]. All these results fully implement within the framework of the vacuum-1 photon QST the original *complete*, i.e., *active* teleportation protocol [1,6]. This method can be easily extended to the other common qubit QST configurations [3,4], where in general two different unitary transformations, and then two different EOP devices are required: $U_j(\sigma_x,\sigma_y)$, $j=1,2$.

Because of the prospective key relevance of the quantum teleportation protocol at the core of many important logic networks [16], the present demonstration is expected to represent a substantial step forward towards the actual implementation of complex multiple qubit gates in the domain of linear optics quantum computation [13,14]. The recent literature shows that the field is indeed moving fast in that direction [17].

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